Continuous-wave laser operation of diode-pumped $Nd:YVO_4/YVO_4$ composite crystal

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Thermal effects control is very critical in highly scaling the output power of diode-pumped solid-state lasers to a few watts especially for end pumping configuration. Low temperature reservation of the pumping surface and the crystal could be adopted to reduce thermal effects and improve laser performance. Diffusion bonding crystal has been demonstrated to be an effective method to relieve the thermal lensing theoretically based on the numerical heat analysis to the end-pumped anisotropic laser crystal. The temperature distribution in $Nd:YVO_4/YVO_4$ composite crystal was analyzed before the end-pumped $Nd:YVO_4/YVO_4$ composite crystal laser with V cavity was designed and set up. The maximum output powers of 9.53 W at 1064 nm, 5.01 W at 532 nm were obtained while the pumping power was 17 W. The highest optical to optical conversion efficiencies were up to 59.1% at 1064 nm and 34.4% at 532 nm, respectively.

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In recent years, high power diode-pumped all-solid-state lasers have attracted much more interest for their unique merits, such as long lifetime, compact structure, high stability, and optical to optical conversion efficiency[1−3]. It is very important to control thermal effects for diode-pumped solid state-lasers to a few watts, especially for end pumping configuration. Large thermal gradient arises from the heat deposition within a very small volume near the pumping facet of the laser crystal in longitudinally pumped system, which resulted in thermal lensing and the strongest aberrations at the pumping facet[4−8]. Low temperature reservation in the crystal body could be adopted to relieve thermal effects and improve laser performance. This can be done by using diffusion bonding of Nd-doped YVO_4 crystal to a non-doped YVO_4 crystal[9−12], which serves as a heat sink for the pumping surface. The impacts of nondoped crystal on doped laser crystals in end pumping configuration was analysed theoretically and verified experimentally in this paper.

The $Nd:YVO_4/YVO_4$ composite crystal used in experiment is shown in Fig. 1. The dimension of the doped $Nd:YVO_4$ and non-doped YVO_4 crystals are 4×4×7 (mm) and 4×4×4 (mm), respectively. The $Nd:YVO_4$ and YVO_4 crystals were a-cut and polished precisely before diffusion bonding of the $Nd:YVO_4$ and YVO_4 crystals togather. Both of the $Nd:YVO_4/YVO_4$ crystal facets were antireflective coated (AR) at 808 and 1064 nm.

A schematic of the laser configuration is shown in Fig. 2. Both of $Nd:YVO_4/YVO_4$ and KTP crystals were water-cooled. The $Nd:YVO_4/YVO_4$ composite crystal was pumped by a fiber coupled diode laser at 808 nm. The radius of the pump beam was compressed to 0.32 mm on interface of the laser crystal. The a-cut $Nd:YVO_4/YVO_4$ composite crystal has a Nd^{3+} concentration of 0.5 at.-%. A V-folded cavity was adopted in this experiment. Flat mirror M1 was AR coated at 1064 and 808 nm as one resonator mirror, the output coupler M2 was a high-reflective (HR) folded mirror with radii of curvature of 100 mm. M3 was a flat mirror coated for HR at 1064 nm and AR at 532 nm. The lengths of arms, L1, L2, were 90 and 52 mm, respectively. The total cavity length should be about 142 mm. A KTP crystal (cut for II-type phase matching, $\theta = 90°$, $\phi = 23.4°$) was used for frequency doubling with dimension of 3×3×10 (mm), and was AR coated at 1064 and 532 nm.

Part of the absorbed pumping energy would be transferred into heat dissipated in the laser crystal due to the quantum defect mechanism. The copper heat sink around the periphery of the composite crystal was water-cooled to keep at a constant temperature. Considering that the thermal conductivity of the heat sink is much greater than that of the crystal. The temperature at the surrounding facets of composite crystal was supposed to be a constant. The heat conduction in the crystal then can be analyzed by the Possion equation as

$$K_x \frac{\partial^2 T(x,y,z)}{\partial x^2} + K_y \frac{\partial^2 T(x,y,z)}{\partial y^2} + K_z \frac{\partial^2 T(x,y,z)}{\partial z^2} + q(x,y,z) = 0, \quad (1)$$

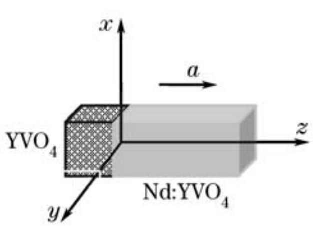

Fig. 1. $Nd:YVO_4/YVO_4$ composite crystal.

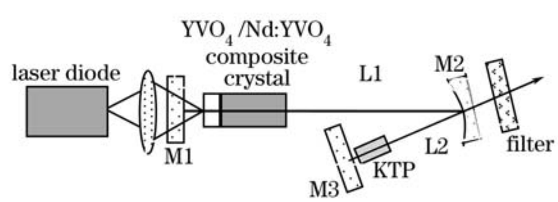

Fig. 2. Schematic of the $Nd:YVO_4/YVO_4$/KTP green light laser.

where $q(x, y, z)$ is the thermal density arising from the pumping power, and K_x, K_y, K_z are the heat conductivities of the crystal at x, y, z orientations. The thermal density $q(x, y, z)$ was assumed to be of Gaussian function along the resonator axis in the crystal[11]

$$q(x,y,z) = \frac{2Q\alpha}{\pi\omega_p^2}(1-\mathrm{e}^{-\alpha l})\mathrm{e}^{-2(x^2+y^2)/\omega_p^2}\mathrm{e}^{-\alpha z}, \qquad (2)$$

where Q is the thermal load contributed from the portion of the incident power entering into the pumped facet, α the absorption coefficient for that pump light, ω_p the Gaussian beam waist, l the crystal length.

Equation (1) can be solved numerically by Dirichlet method[13]. Suppose that the heat sink temperature is remained at $T_0 = 293$ K, both front and end facets of the composite crystal were heat-insulated as they were directly exposed to air. The thermal distribution in the $Nd:YVO_4/YVO_4$ composite crystal was numerically calculated under the condition of 18-W pumping power and 0.32-mm pumping beam radius. The results were showed in Figs. 3 and 4.

The highest temperatures on the pumping surface of the $Nd:YVO_4/YVO_4$ composite and $Nd:YVO_4$ crystal were 425 and 640 K, corresponding to temperature rising of 136 and 351 °C respectively. The thermal distortion of laser crystal dl at z-orientation can be expressed as

$$\mathrm{d}l = \alpha_z\,(u(x,y,z) - u(0))\,\mathrm{d}z. \qquad (3)$$

So the total thermal distortion was

$$\Delta l = \alpha_z \int_0^c \mathrm{d}l = \alpha_z \int_0^c u(x,y,z) - u(0)\mathrm{d}z, \qquad (4)$$

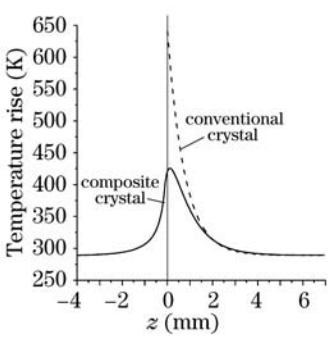

Fig. 3. Comparison of distribution of thermal field of the composite crystal with the conventional crystal.

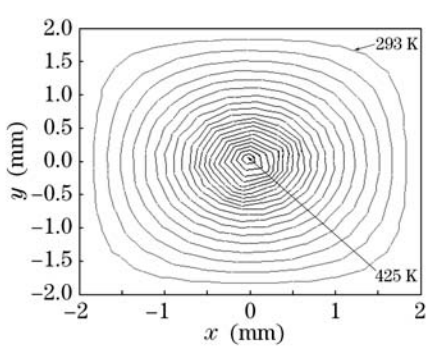

Fig. 4. Isotherm distribution of a $Nd:YVO_4/YVO_4$ composite crystal at x-y section in $z = 0$.

where α_z was the thermal expansion coefficient. $\alpha_z = 11.37 \times 10^{-6}$ K was used for $Nd:YVO_4$ and $Nd:YVO_4/YVO_4$ composite crystal in the calculation. The maximum thermal distortions of 2.85 and 0.736 μm were obtained in the centre of the pumping end surface of $Nd:YVO_4$ and $Nd:YVO_4/YVO_4$ composite crystal respectively at the incident power of 15 W as shown in Fig. 5. The $Nd:YVO_4$/ YVO_4 composite crystal was obviously shown to be a effective method to relieve the thermal dissipation.

The laser performance was investigated experimentally. The oscillation threshold was about 0.5 W, the maximum output power of 5.32 W for continuous wave (CW) $Nd:YVO_4/YVO_4$/KTP green laser has been obtained at the incident pump power of 17 W as shown in Fig. 6.

The green laser operated at TEM_{00} mode while raising the LD pumping power. The output power fluctuation $\Delta\bar{P}$ of the lasers was tested with LP-3C power meter at 1064 and 532 nm while the incident power operated at 10 W. The laser power was measured at a time interval of 6 minutes, as shown in Fig. 7. $\Delta\bar{P}$ was given by

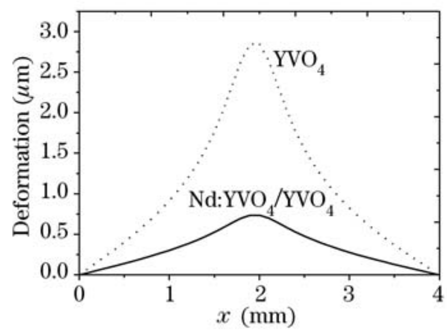

Fig. 5. Thermal distortion of pumping surgace of $Nd:YVO_4$ and $Nd:YVO_4/YVO_4$ composite crystal with pump power of 15 W.

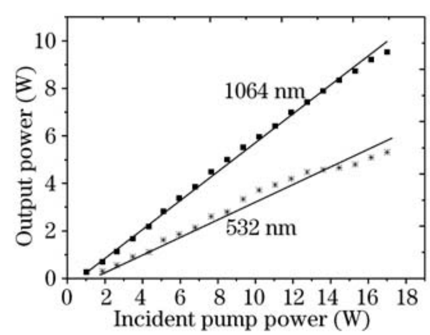

Fig. 6. Average output power at 1064 and 532 nm as a function of incident pump power.

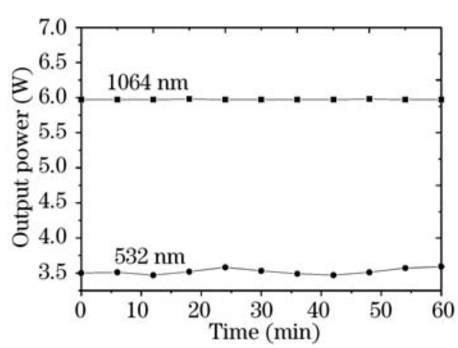

Fig. 7. Output power of 1064 and 532 nm versus time.

$$\Delta\,\bar{P} = \left[\sum_{i-1}^{n}(P_i - \bar{P})^2/n\right]^{1/2}. \quad (5)$$

The stabilities $\Delta\bar{P}/\bar{P}$ of the laser at 1064 and 532 nm were 0.07% and 1.2% respectively.

In summary, thermal effect in LD end pumped solid state laser had been fully investigated numerically and experimentally in this paper. The heat deposition in Nd:YVO_4 crystal and Nd:YVO_4/YVO_4 composite crystals were analysed and compared, laser performance was tested to verify our results. A diode end pumped Nd:YVO_4/YVO_4 composite crystal green laser was designed by intracavity frequency doubling with KTP. The maximum output powers of 9.53 W at 1064 nm, 5.32 W at 532 nm were obtained at the pumping power of 17 W. The highest optical-optical conversion efficiencies were 59.1% at 1064 nm and 34.4% at 532 nm, respectively.

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